

New theory studies for pp scattering

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Outline :

- Near-term prospects for measuring Δg at RHIC
 - * high- p_T jet / hadron production
 - * sign of Δg ?
- Single transverse-spin asymmetries

Near-term prospects for measuring Δg

– High- p_T jets and hadrons –

$$p_T^3 \frac{d\Delta\sigma}{dp_T d\eta} = \left| \begin{array}{c} \text{Diagram showing two incoming protons (p) interacting via fragmentation functions } f_a \text{ and } f_b \text{ to form a central system } \hat{\sigma} \text{ which then decays into a hadron (h) via fragmentation function } D_c^h. \\ \text{The diagram also shows a gluon exchange between the central system and the hadron.} \end{array} \right|_2 + \mathcal{O}\left(\frac{\lambda}{p_T}\right)^n$$

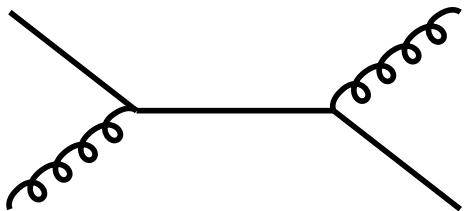
$$d\Delta\sigma^{pp \rightarrow hX} = \sum_{abc} \Delta f_a \otimes \Delta f_b \otimes d\Delta\hat{\sigma}^{ab \rightarrow cX'} \otimes D_c^h + \text{P.C.}$$

$\Delta\hat{\sigma}^{(0)} + \alpha_s \Delta\hat{\sigma}^{(1)} + \dots \text{ pert.}$
LO NLO

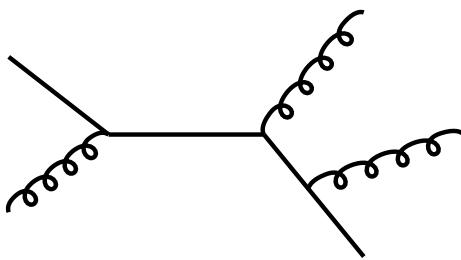


- nucleon spin structure $\Delta f_{a,b}$
- for hadrons : fragmentation functions $D_c^h \sim e^+e^- \text{ annihilation}$

- NLO = state of the art



LO



NLO

- lowest order : good for qualitative descriptions
- however, precise predictions afford higher-order NLO calculations :
 - may be sizeable, in particular in polarized case
 - reduction in scale dependence

$$\mu \frac{d}{d\mu} d\sigma_{\text{phys}} = 0$$

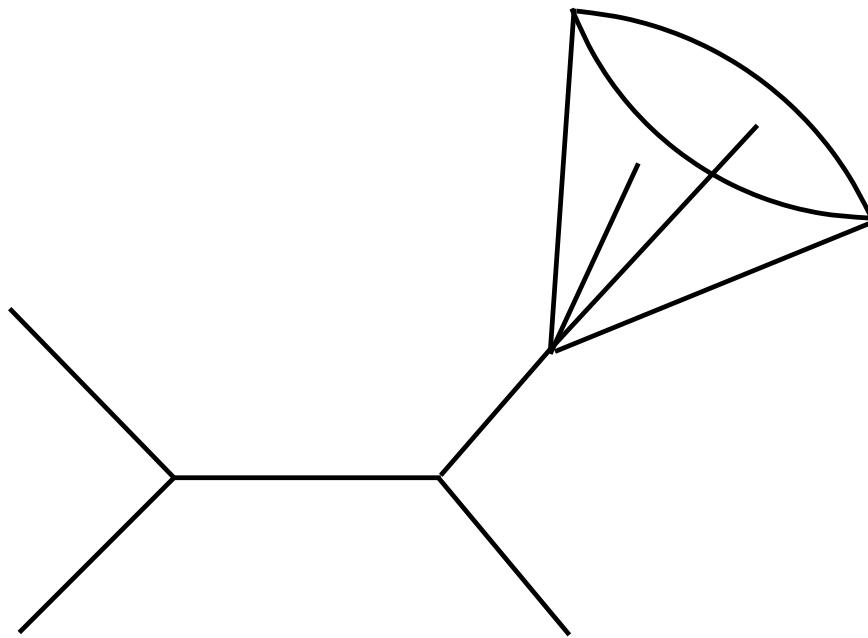
$\neq 0$ in truncated perturbation theory

- NLO corrections now known for all relevant reactions

Gordon,WV; Contogouris et al.; de Florian,Frixione, Signer,WV; Stratmann,Bojak;
de Florian; Jäger,Schäfer,Stratmann,WV; . . .

- jet and hadron calculations share many features

- however :

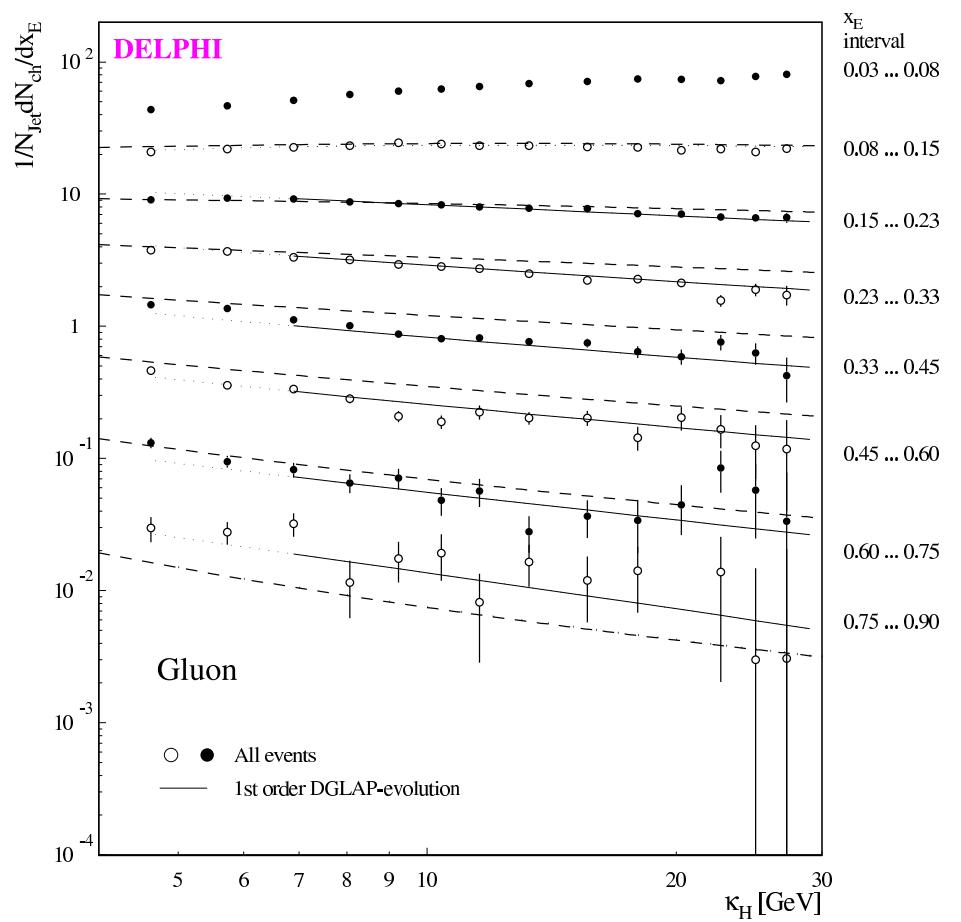
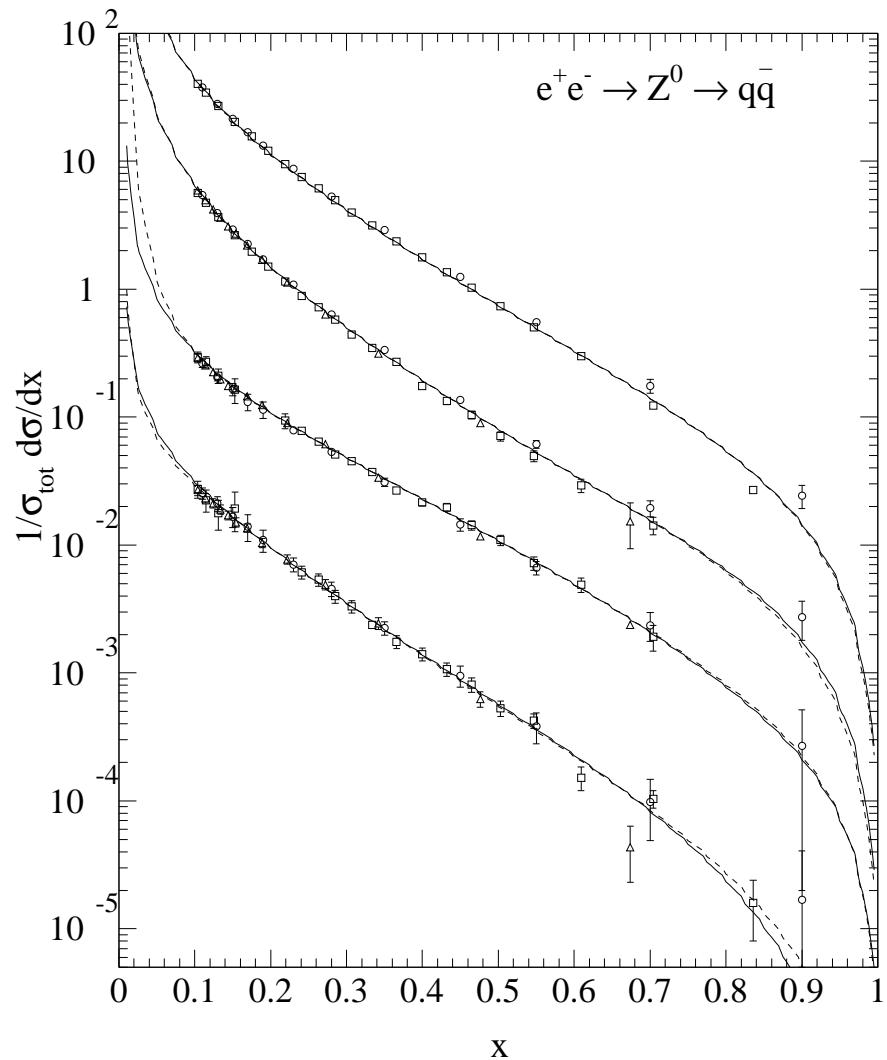


- final-state singularities . . .

. . . cancel for jets

. . . imply additional non-perturbative input for incl. hadrons
→ fragmentation functions

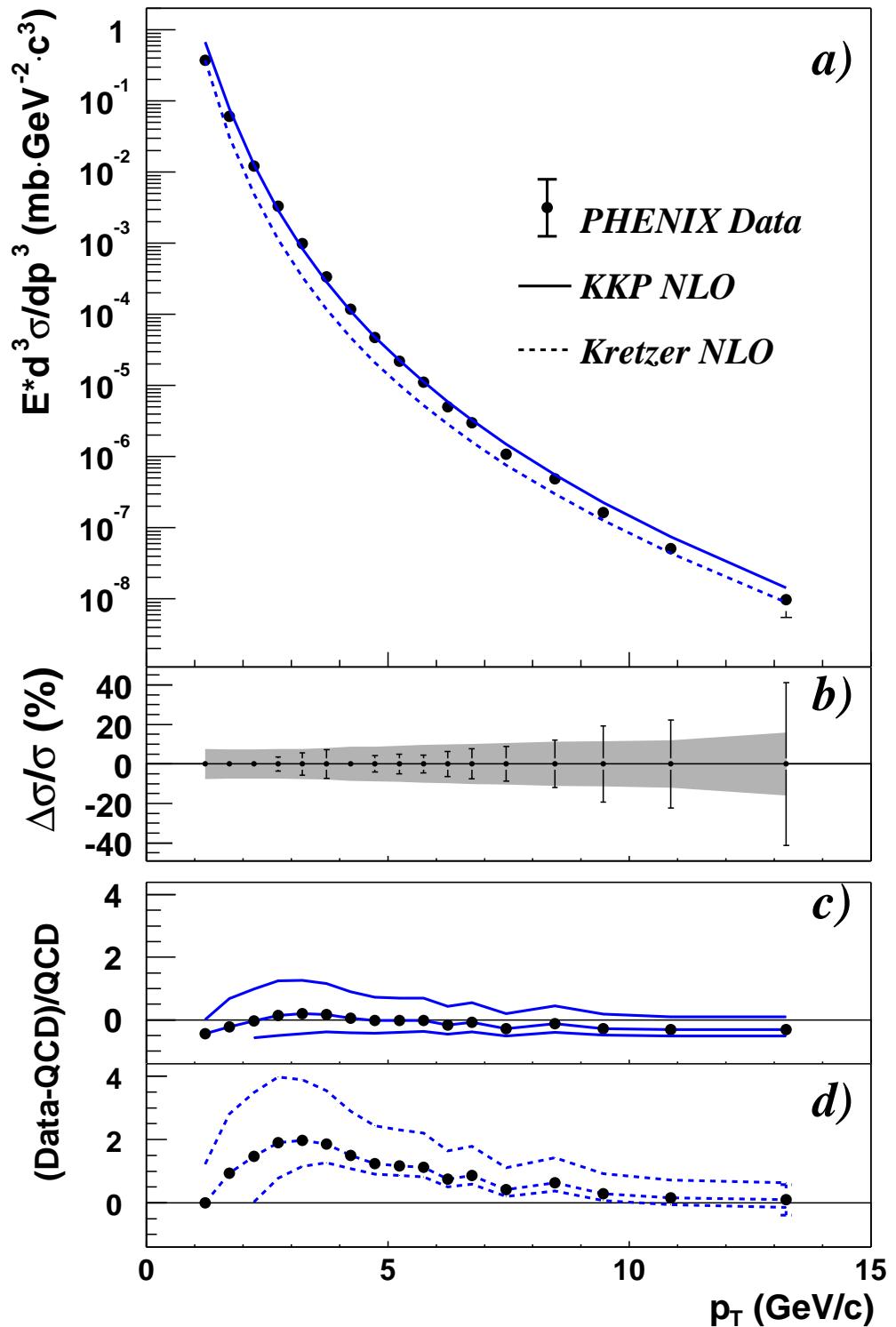
- fragm. fct. analyses : Kniehl,Kramer,Pötter and Kretzer

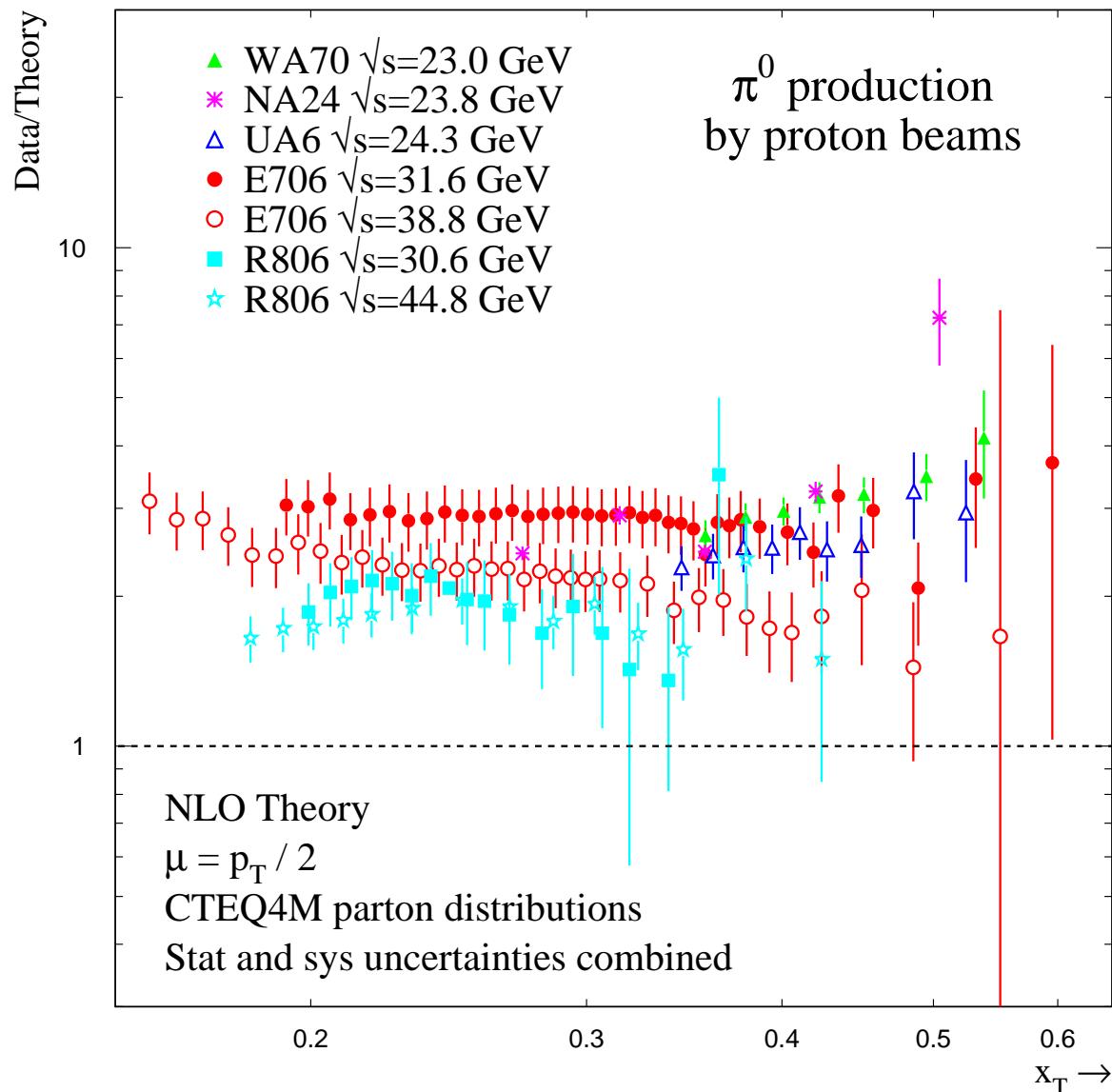


Unpolarized cross section

$pp \rightarrow \pi^0 X$ by
PHENIX

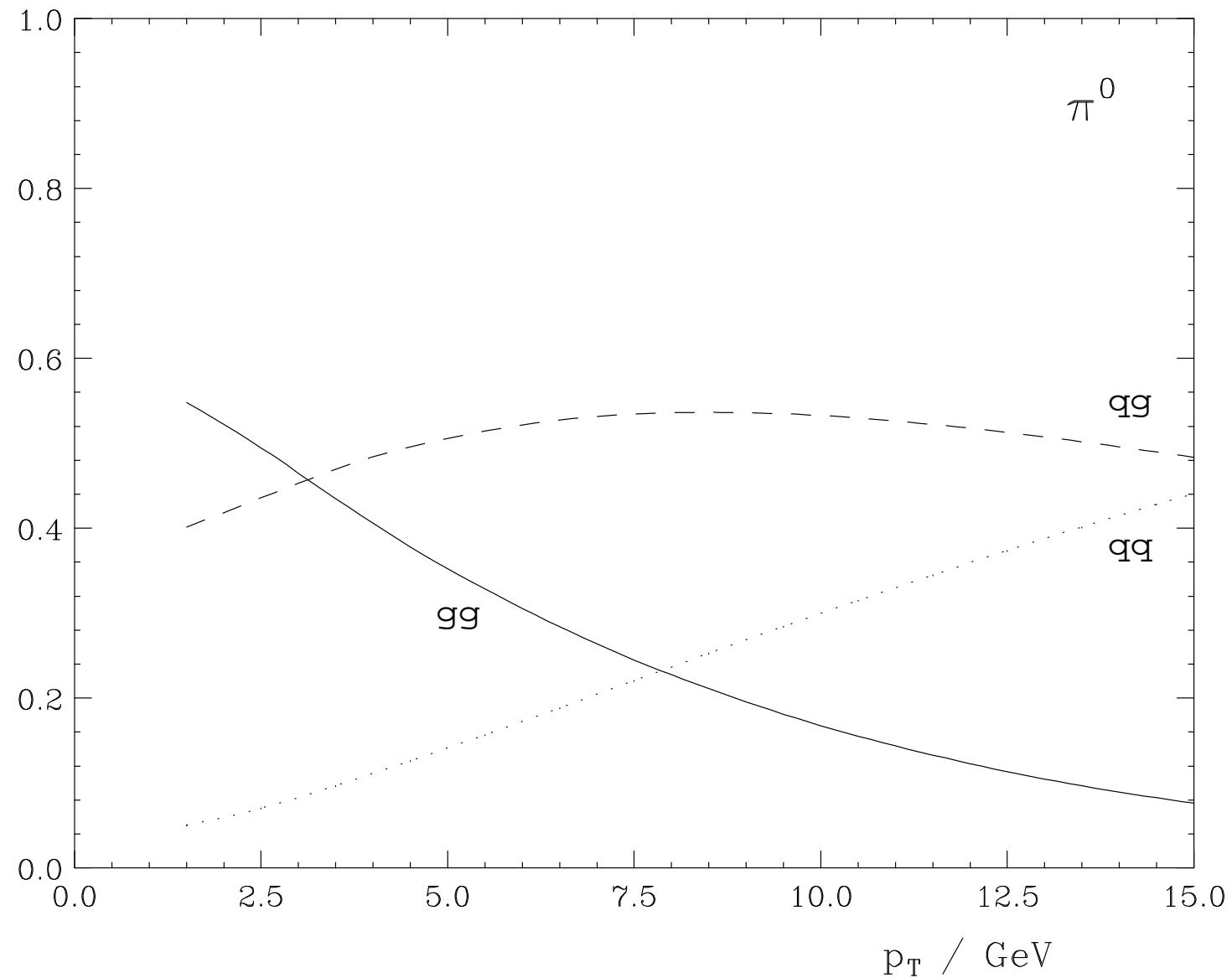
(Why so good . . . ?)



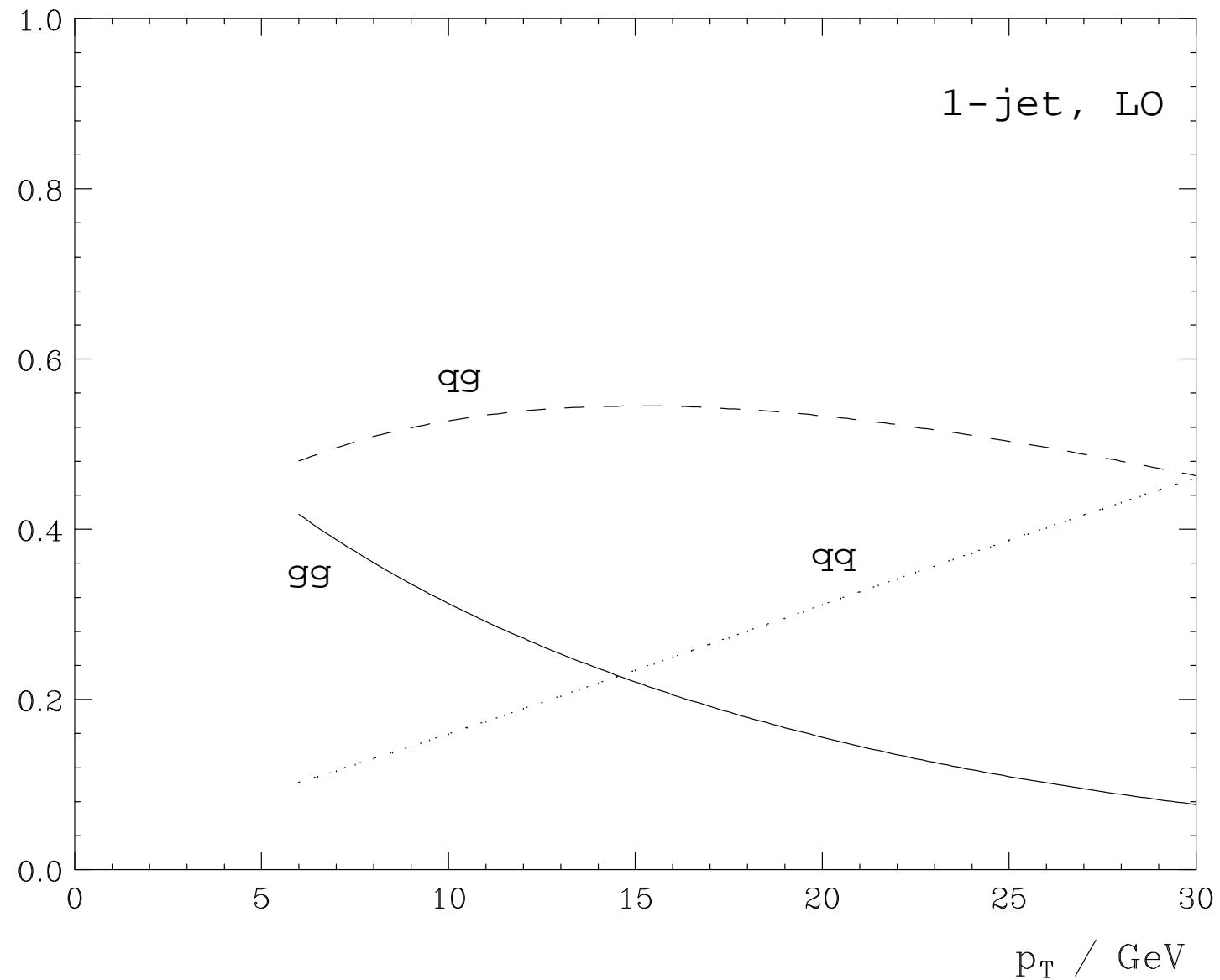


Apanasevich et al. (see also : Aurenche et al.)

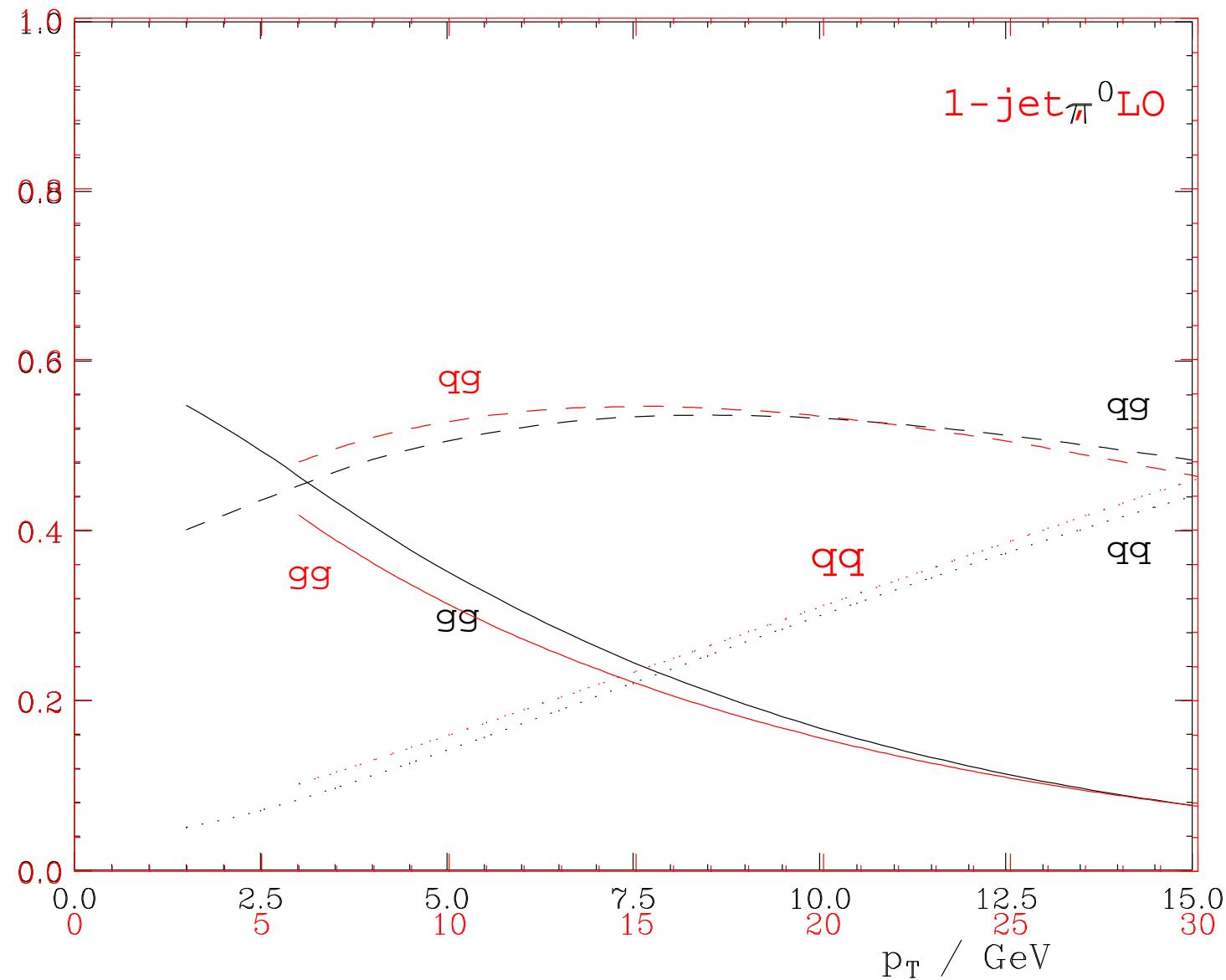
- contributions by partonic scatterings : pions



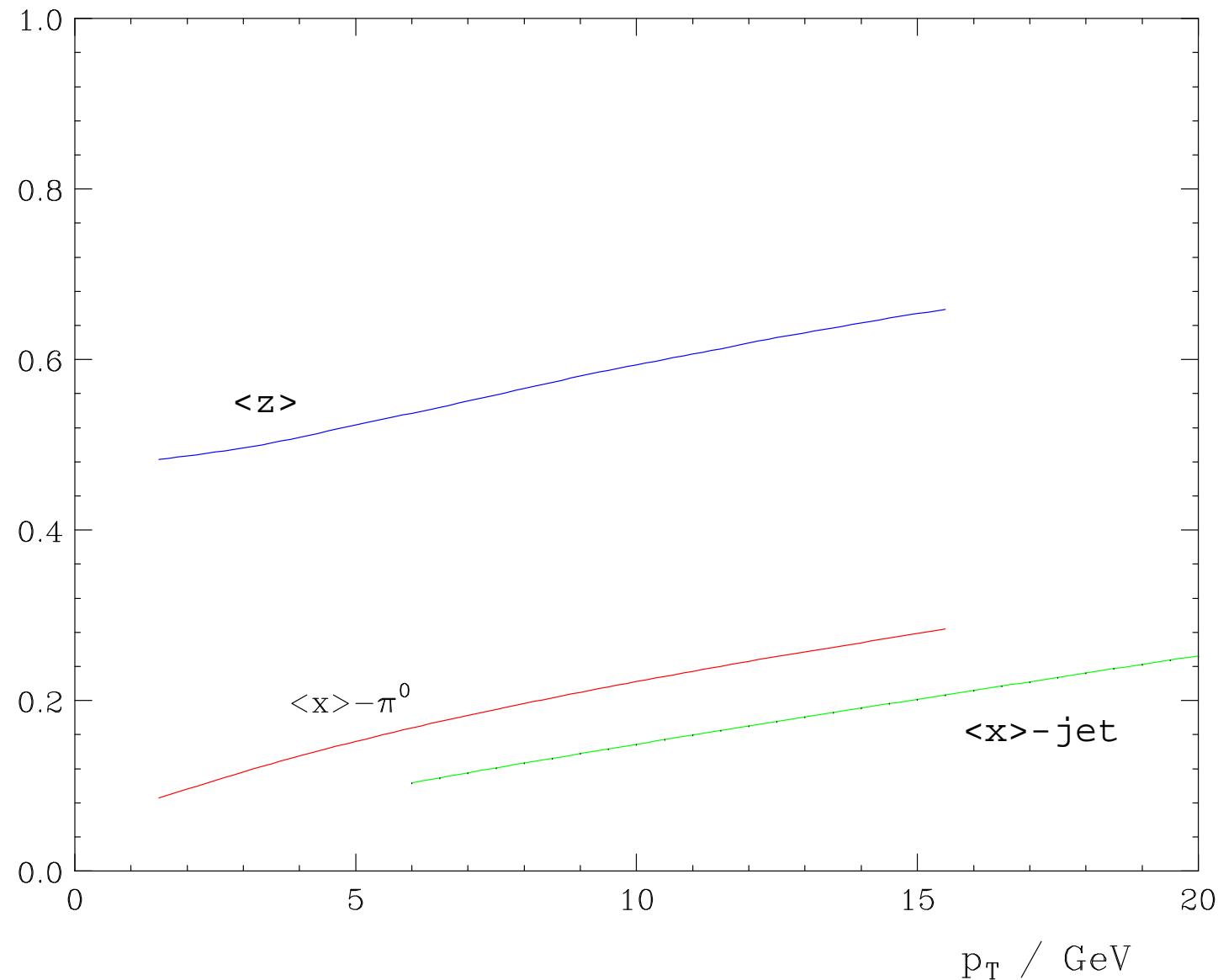
- contributions by partonic scatterings : jets

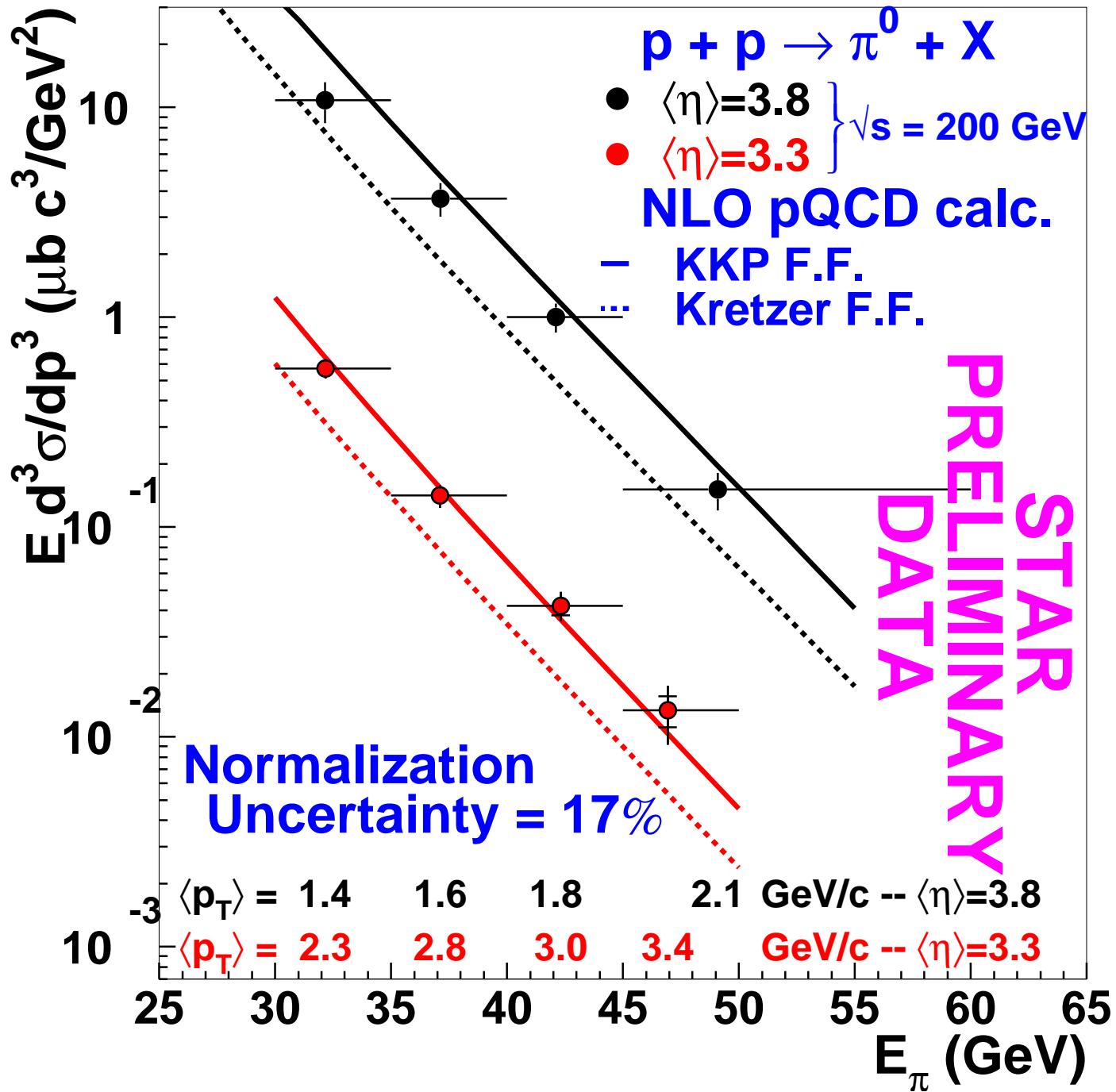


- contributions by partonic scatterings :



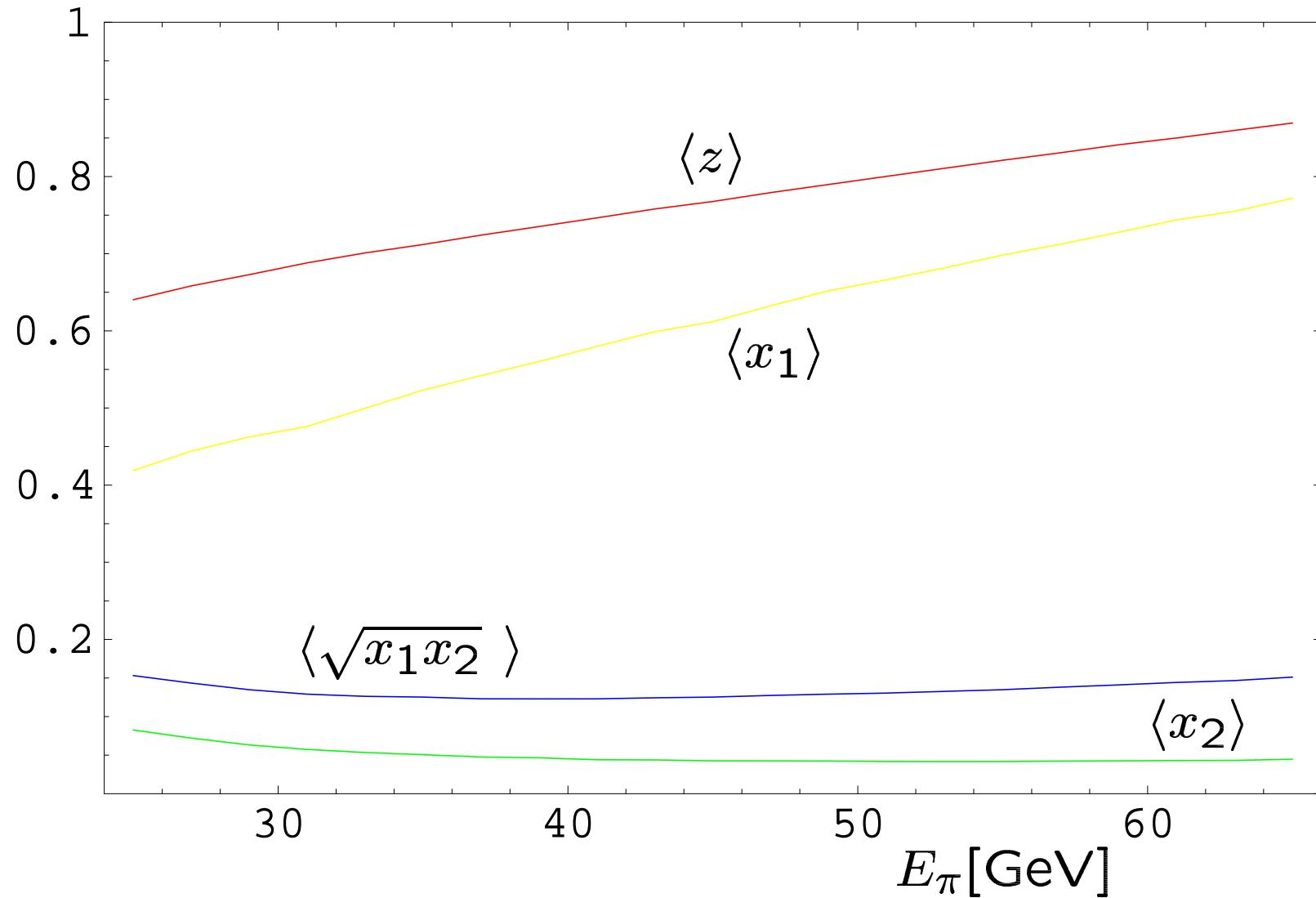
- average x and z :



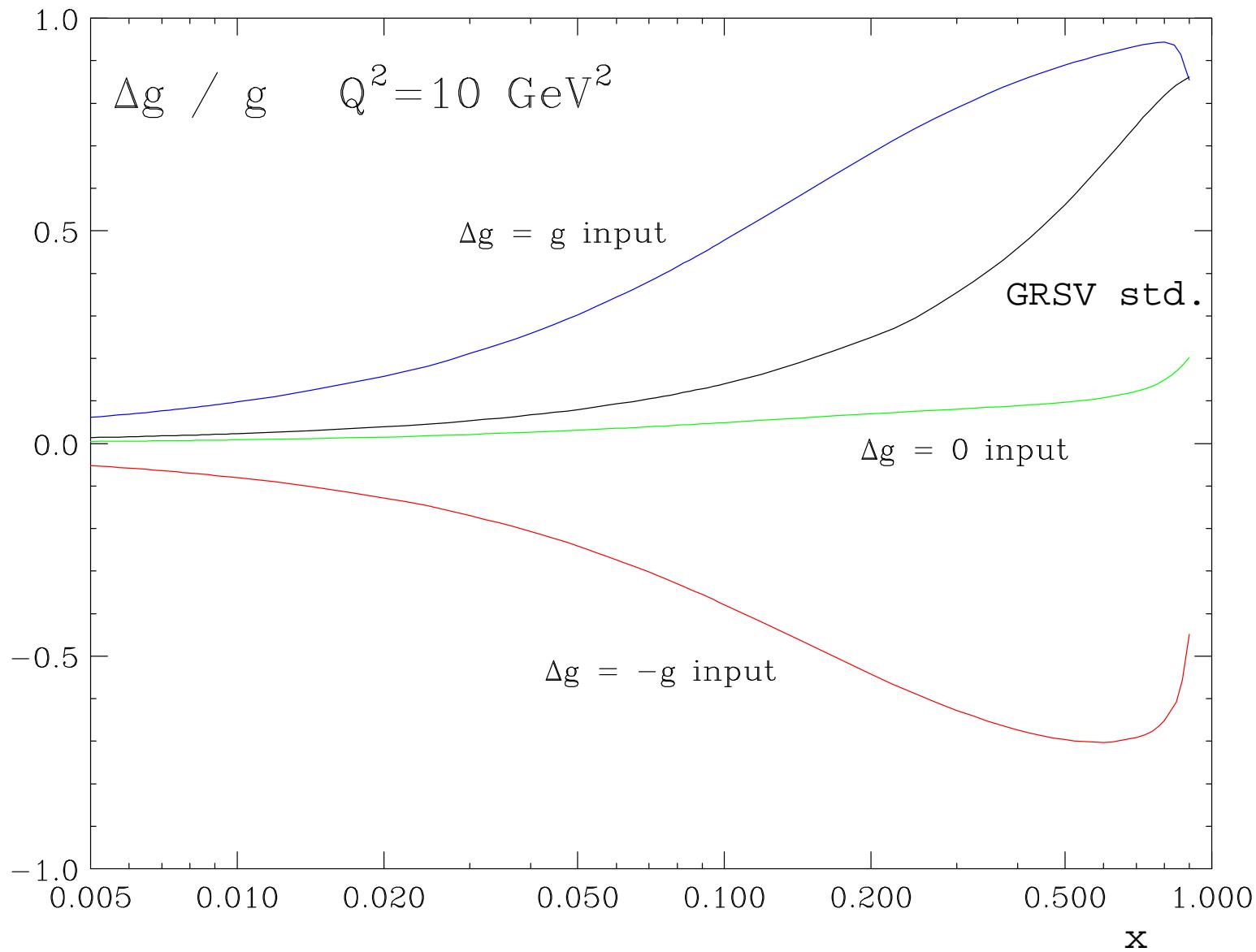


- average x and z in forward region :

Kretzer



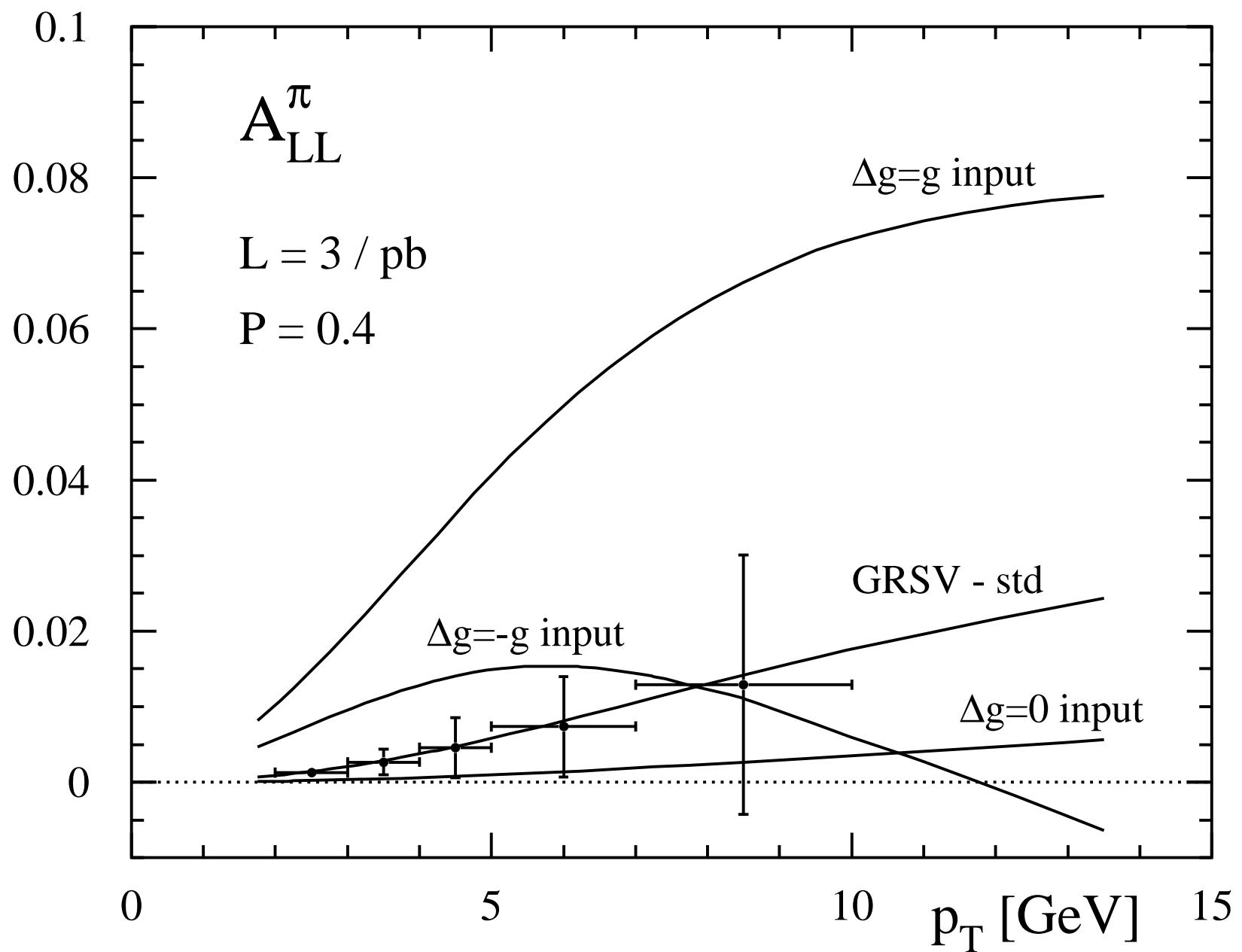
Spin asymmetry



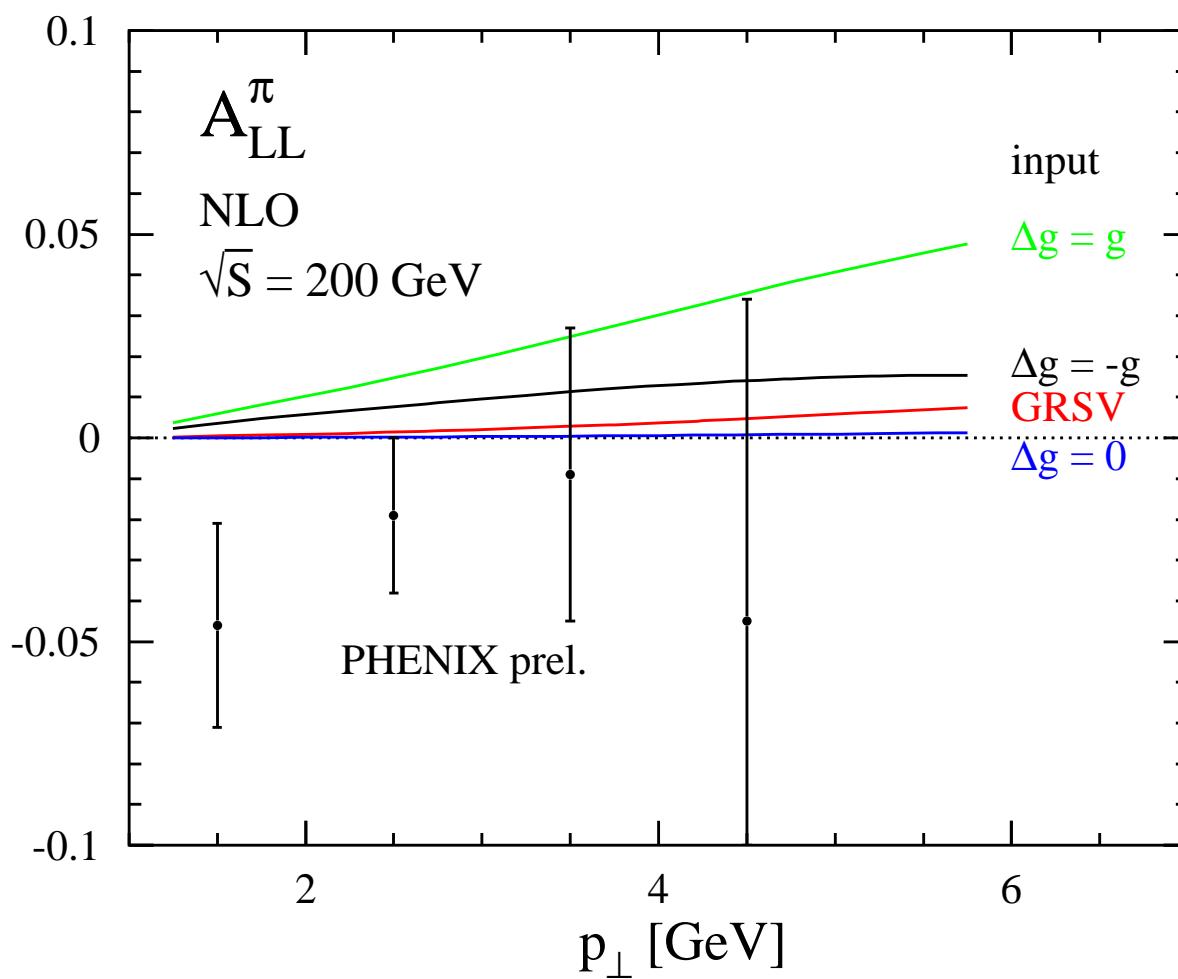
Polarized gluon densities : Glück,Reya,Stratmann,WV

$pp \rightarrow \pi^0 X, \sqrt{S} = 200 \text{ GeV}, |\eta| \leq 0.38$

Jäger, Schäfer, Stratmann, WV



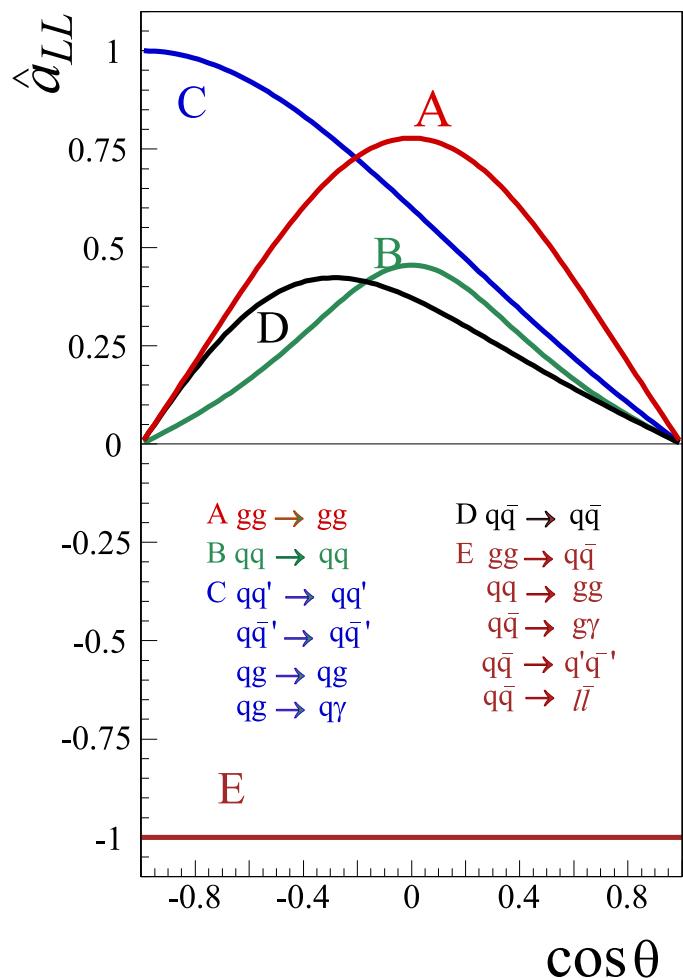
- latest development : first preliminary data from **PHENIX** !



- \Rightarrow can A_{LL}^π be negative ? How negative can it be ?

- partonic subprocess asymmetries

$$\hat{a}_{LL} \equiv \frac{\hat{\sigma}_{++} - \hat{\sigma}_{+-}}{\hat{\sigma}_{++} + \hat{\sigma}_{+-}}$$



- $gg \rightarrow q\bar{q}$ has negative \hat{a}_{LL}
- however, $\hat{\sigma}_{gg \rightarrow gg} \approx 160 \times \hat{\sigma}_{gg \rightarrow q\bar{q}}$ (at $\hat{\eta} = 0$)

A lower bound on A_{LL}^π

Jäger,Kretzer,Stratmann,WV

- integrate LO cross section over all rapidities $|\eta| \leq \cosh^{-1}(x_T)$,
and take mellin moments in $x_T^2 \equiv 4p_\perp^2/S$:

$$\Delta\sigma^\pi(N) \equiv \int_0^1 dx_T^2 (x_T^2)^{N-1} \frac{p_\perp^3 d\Delta\sigma^\pi}{dp_\perp}$$

- obtain

$$\Delta\sigma^\pi(N) = \sum_{a,b,c} \Delta f_a^{N+1} \Delta f_b^{N+1} \Delta \hat{\sigma}_{ab}^{c,N} D_c^{\pi,2N+3}$$

- in terms of moments of Δg :

$$\Delta\sigma^\pi(N) = (\Delta g^{N+1})^2 \mathcal{A}^N + 2 \Delta g^{N+1} \mathcal{B}^N + \mathcal{C}^N$$


 $gg \text{ scatt.}$ qg $qq, qq', q\bar{q}, \dots$

- a parabola – with a minimum given by

$$\mathcal{A}^N \Delta g^{N+1} = -\mathcal{B}^N$$

$$\Delta\sigma^\pi(N) \Big|_{\min} = -\frac{(\mathcal{B}^N)^2}{\mathcal{A}^N} + \mathcal{C}^N$$

- Mellin inverse :

$$\frac{p_\perp^3 d\Delta\sigma^\pi}{dp_\perp} \Big|_{\min} = \frac{1}{2\pi i} \int_{\Gamma} dN (x_T^2)^{-N} \Delta\sigma^\pi(N) \Big|_{\min}$$

- resulting asymmetry : negative, but tiny

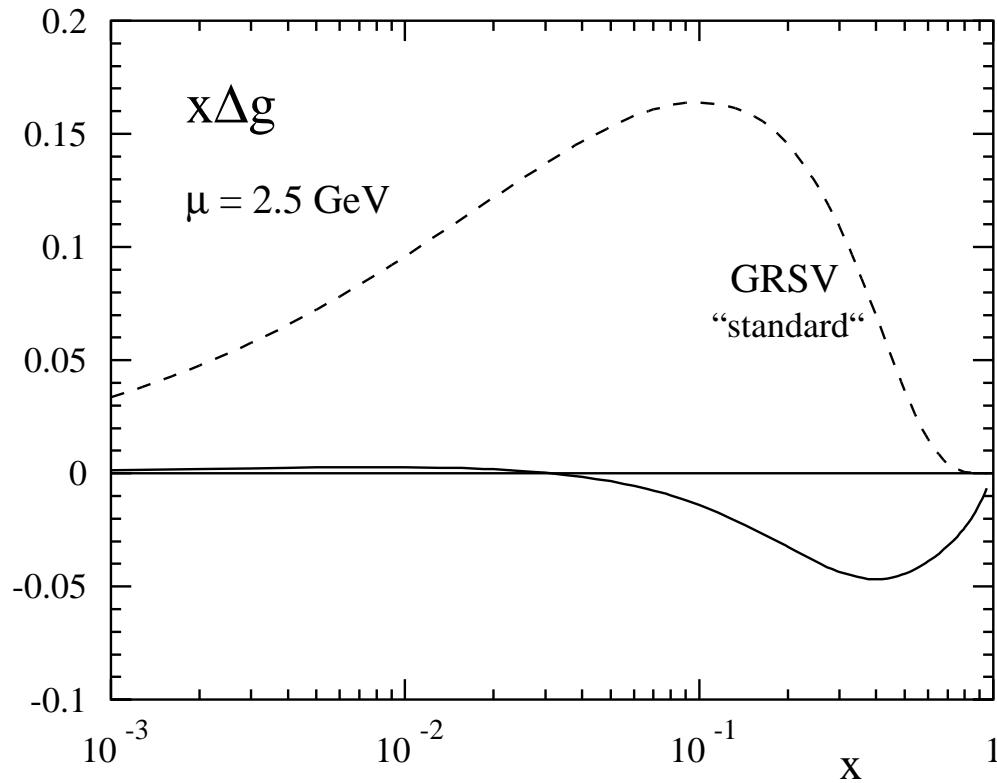
$p_\perp = 1.5 \text{ GeV} :$

$A_{\text{LL}}^\pi \approx -10^{-4}$

$p_\perp = 4.5 \text{ GeV} :$

$A_{\text{LL}}^\pi \approx -10^{-3}$

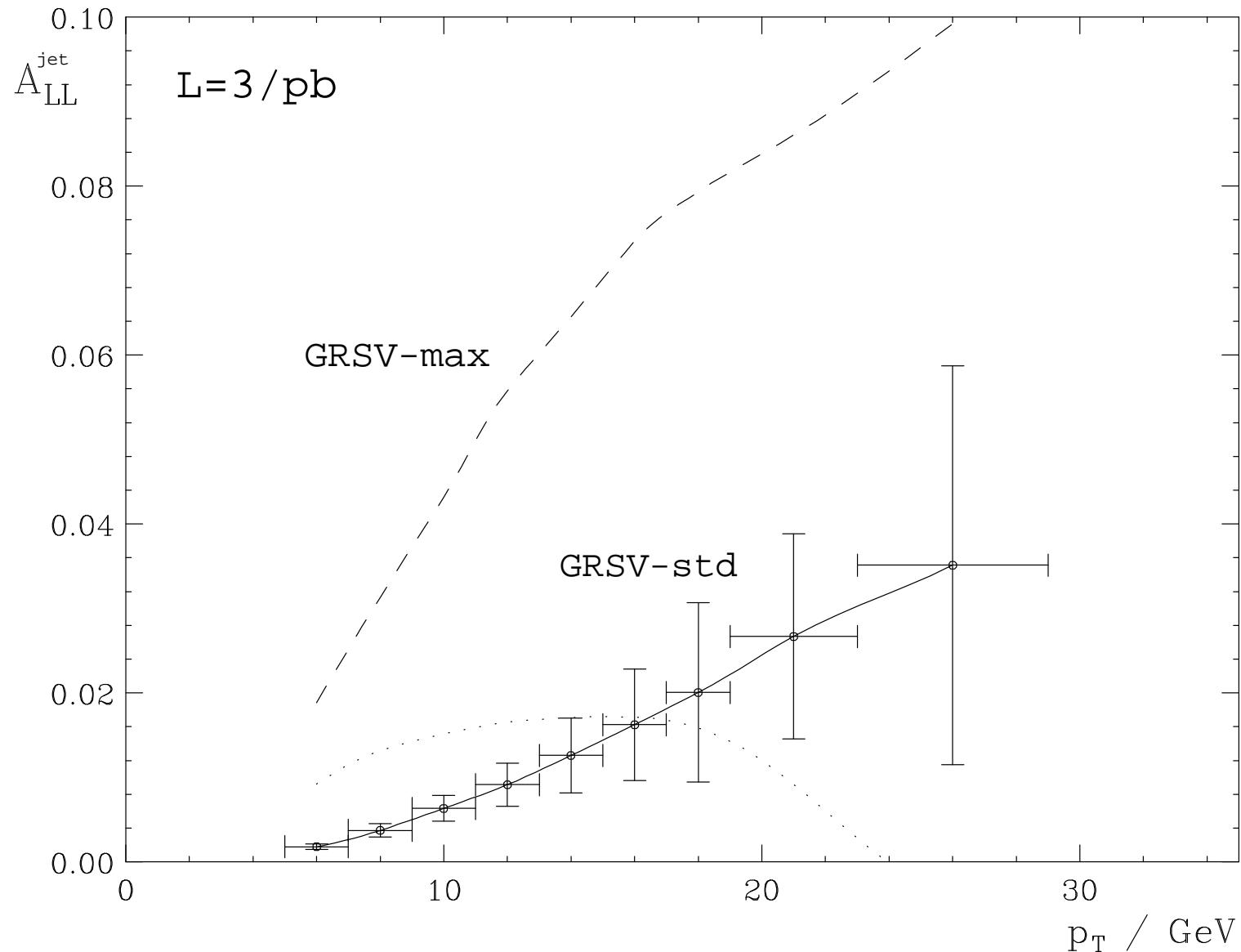
- the polarized gluon that minimizes A_{LL}^π :



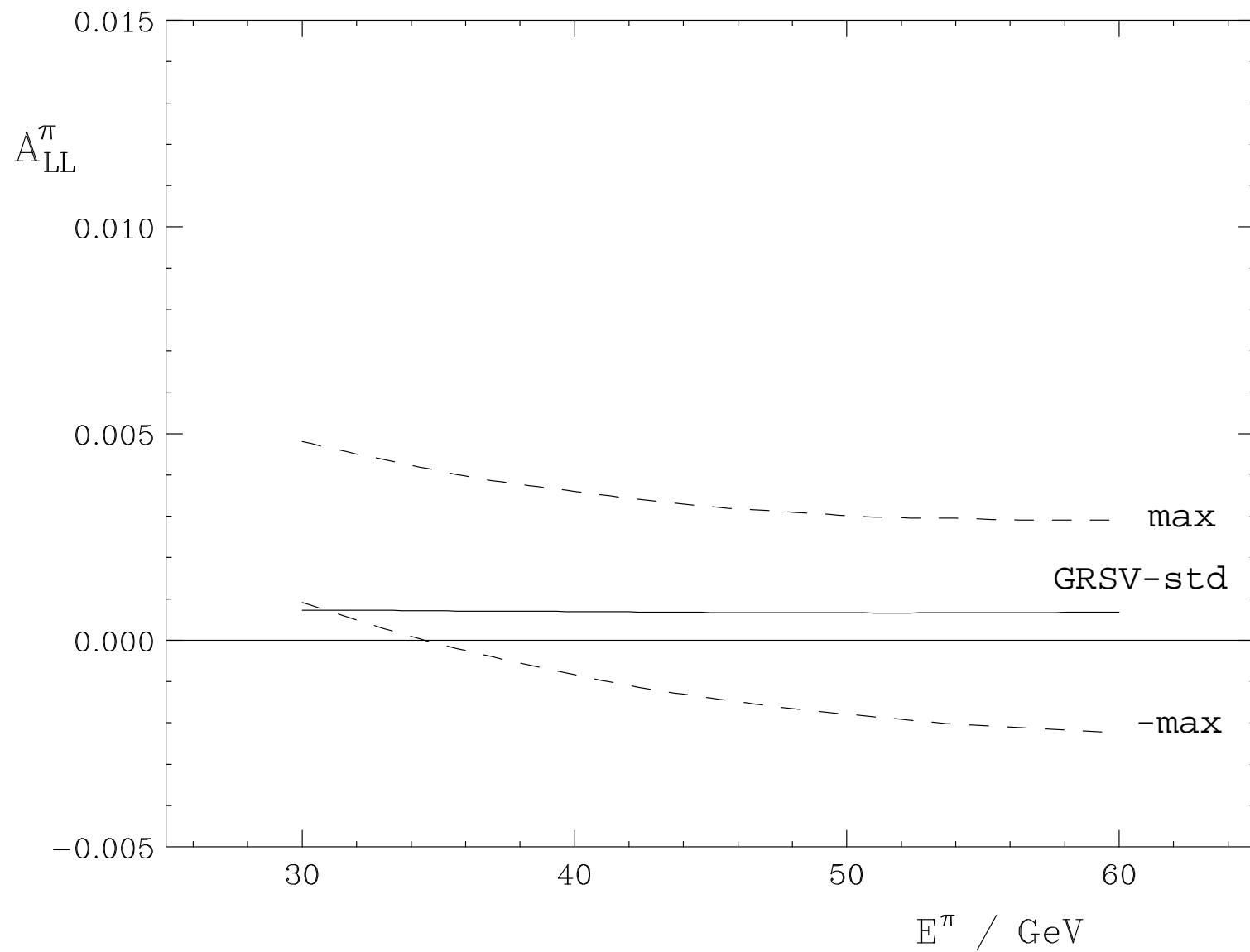
- a node – helps by allowing $\Delta g(x_a) \times \Delta g(x_b) < 0$
- a full “global analysis” confirms :
pQCD at leading power predicts that a negative A_{LL}^π is small

$pp \rightarrow \text{jet}X, \sqrt{S} = 200 \text{ GeV}, 0 \leq \eta \leq 1$

de Florian,Frixione,Signer,WV



$pp \rightarrow \pi^0 X, \sqrt{S} = 200 \text{ GeV}, \eta = 3.3$

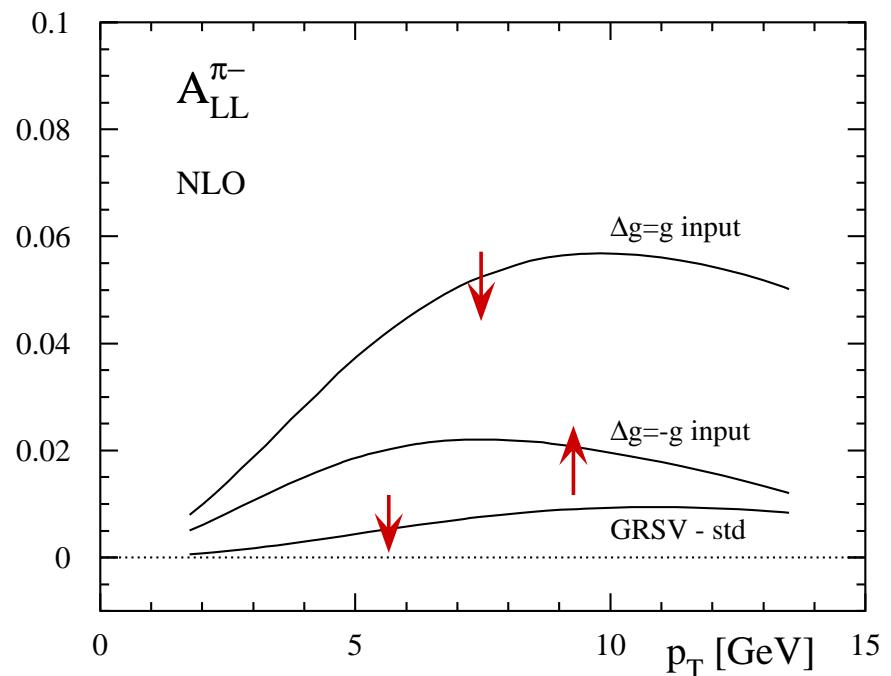
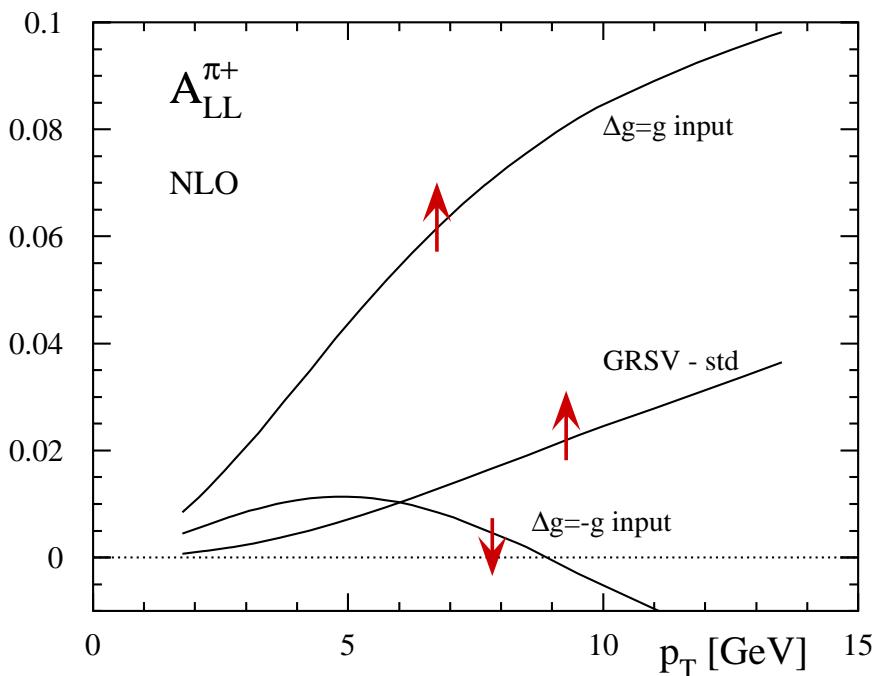


- dominance of $qg \rightarrow qg$ sets in

π^+ and π^-

positive Δg : $A_{LL}^{\pi^+} > A_{LL}^{\pi^0}$
negative Δg : $A_{LL}^{\pi^+} < A_{LL}^{\pi^0}$

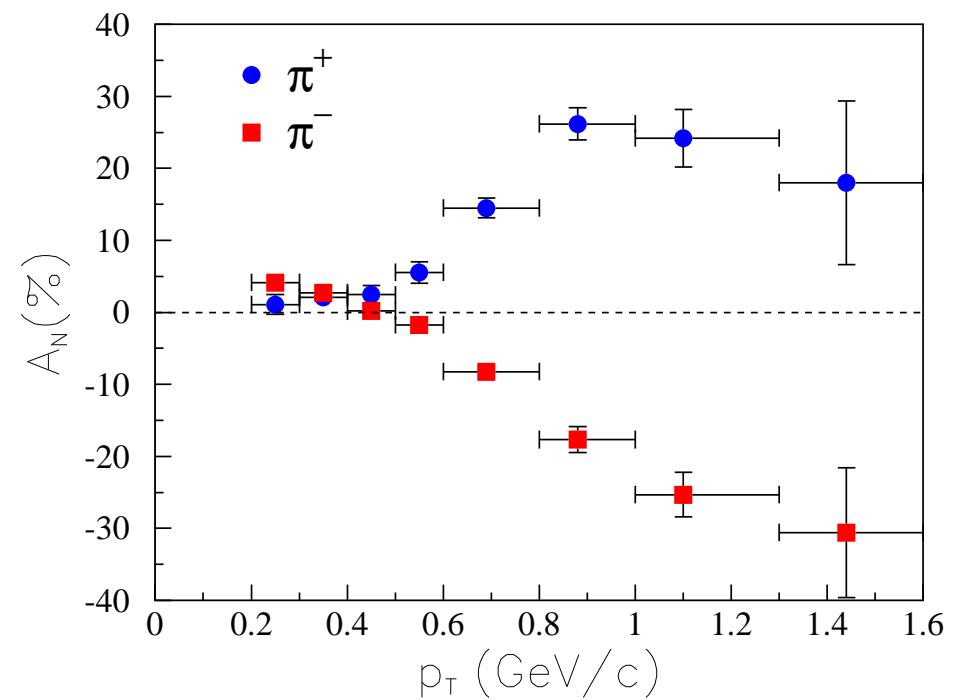
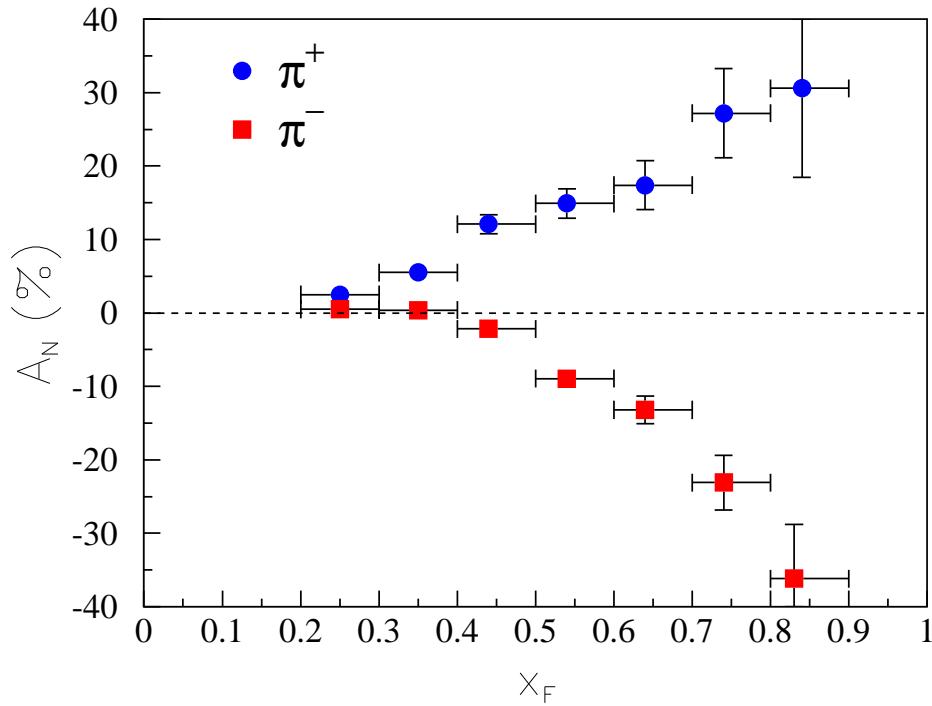
positive Δg : $A_{LL}^{\pi^-} < A_{LL}^{\pi^0}$
negative Δg : $A_{LL}^{\pi^-} > A_{LL}^{\pi^0}$



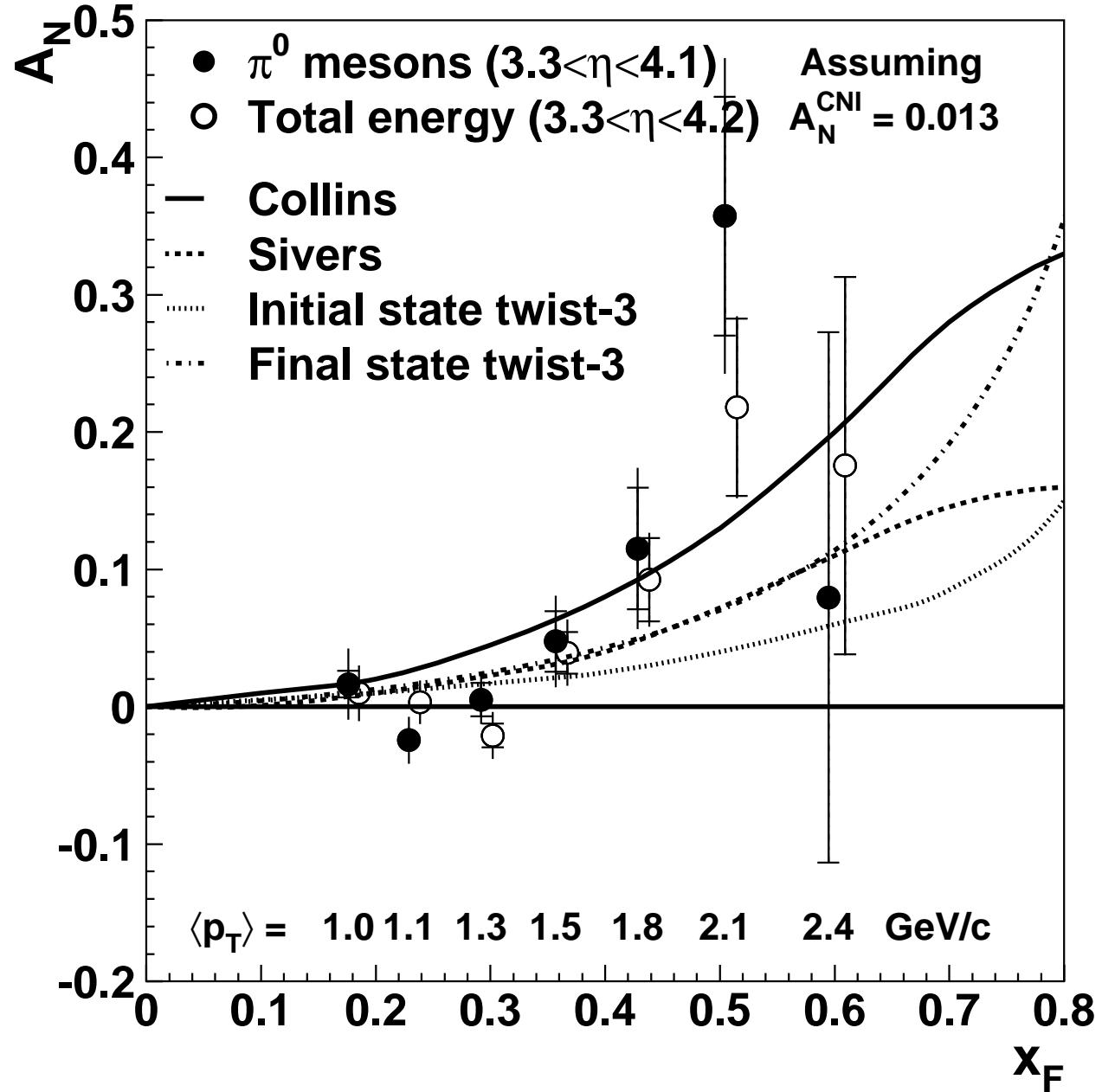
... only at $p_T > 5$ GeV, good statistics required

Single-transverse spin asymmetry A_N

- correlation $\sim i \vec{s}_T \cdot (\vec{p}_{\text{beam}} \times \vec{l}_\pi)$
- * large A_N seen in fixed-target experiments at **BNL,ANL,Fermilab,Serpukhov**
- * E704 ('96) :



- A_N is power-suppressed as $1/p_T$. . .



* higher p_T : see expected $1/p_T$ behavior ?

- Sivers '90 :

$$f_{1T}^\perp = \frac{P}{S_T} - \text{[diagram difference]}$$

asymmetry

$$q_{p\uparrow}(x, \vec{k}_T) \neq q_{p\uparrow}(x, -\vec{k}_T)$$

- mechanism is

$$A_N \propto f_{1T}^\perp(x_a, k_\perp) q(x_b) \hat{\sigma}^{qq \rightarrow qq}(k_\perp) D(z)$$

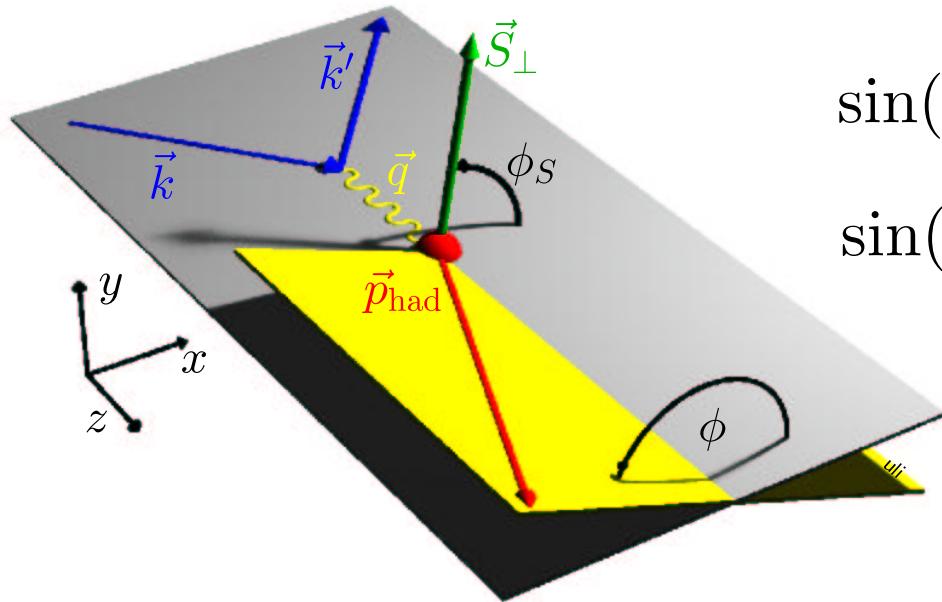
- however Collins '93 : for distribution functions correlation
 $\vec{S}_T \cdot (\vec{P} \times \vec{k}_T)$ ruled out by T invariance of QCD
- recent development : gauge links that make pdfs *gauge invariant* allow the “T-odd” structure

(Brodsky,Hwang,Schmidt; Collins; Belitsky,Ji,Yuan; Boer,Mulders,Pijlman)

- A_N for a single-inclusive observable :
 - * interpretation complicated : Sivers vs Collins vs Qiu/Sterman,Koike
 - * $p^\uparrow p \rightarrow \gamma X, p^\uparrow p \rightarrow \mu^+ \mu^- X, p^\uparrow p \rightarrow \text{jet } X \dots$
 - * factorization with k_\perp an *assumption*
- there is a class of observables that depend directly on a measured k_T :
 - * azimuthal asymmetries in $ep^\uparrow \rightarrow e' \pi X$
 - * azimuthal asymmetries in $e^+ e^- \rightarrow \pi \pi X$
 - * $p^\uparrow p$ scattering ?
- for these, k_\perp effects are not power-suppressed, and more experience with factorization is available

- example : $ep^\uparrow \rightarrow e\pi X$

Collins



$$\sin(\phi + \phi_S) \sum_q e_q^2 \delta q(x) H_1^{\perp,q}(z)$$

$$\sin(\phi - \phi_S) \sum_q e_q^2 f_{1T}^{\perp,q}(x) D_q(z)$$

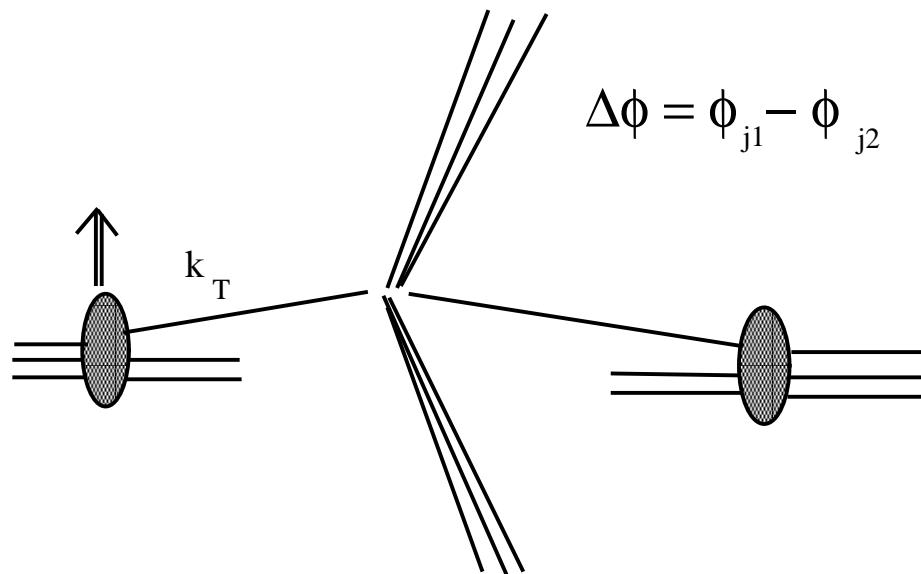
- HERMES

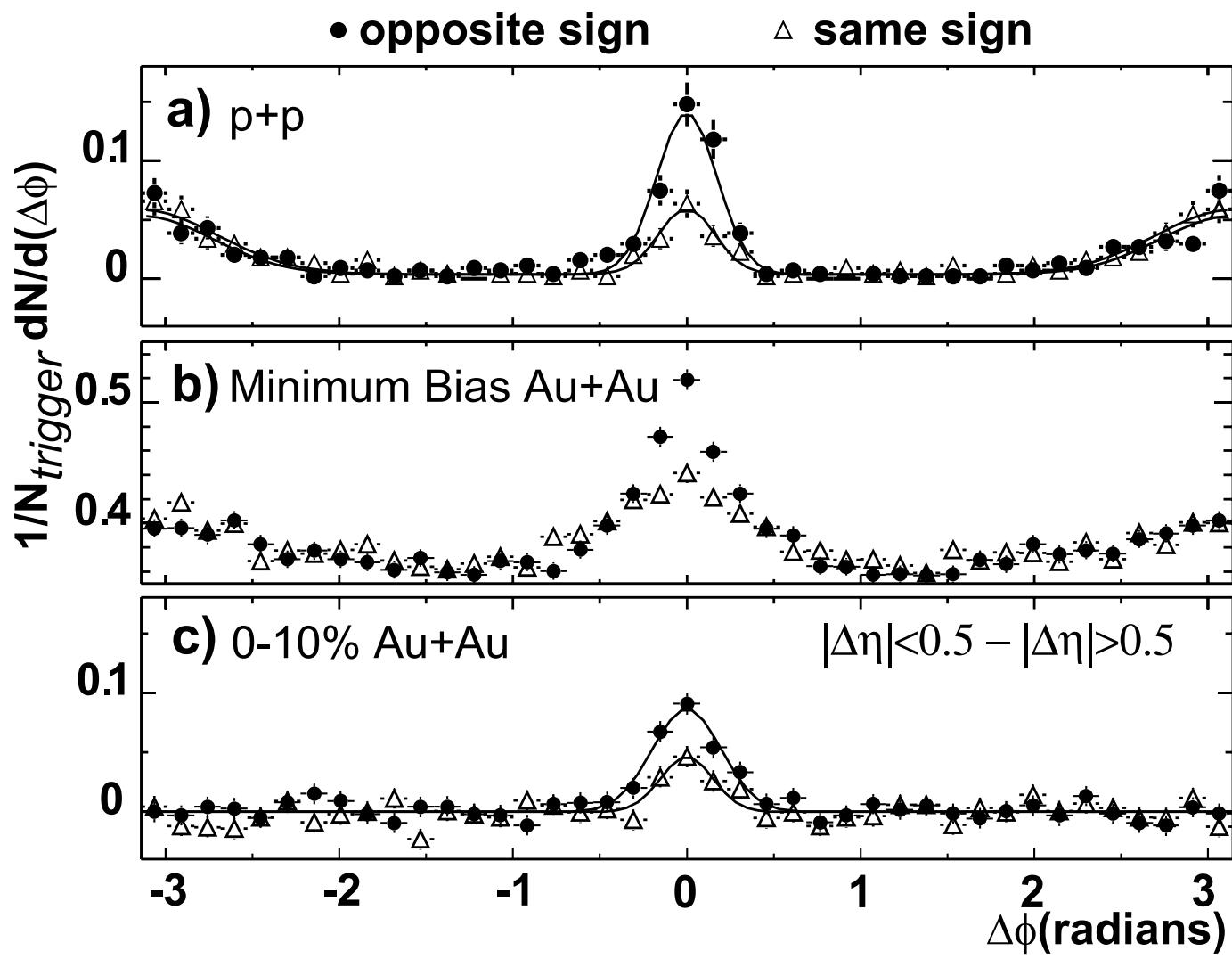
- only moderate Q^2

What's a similar observable in pp ?

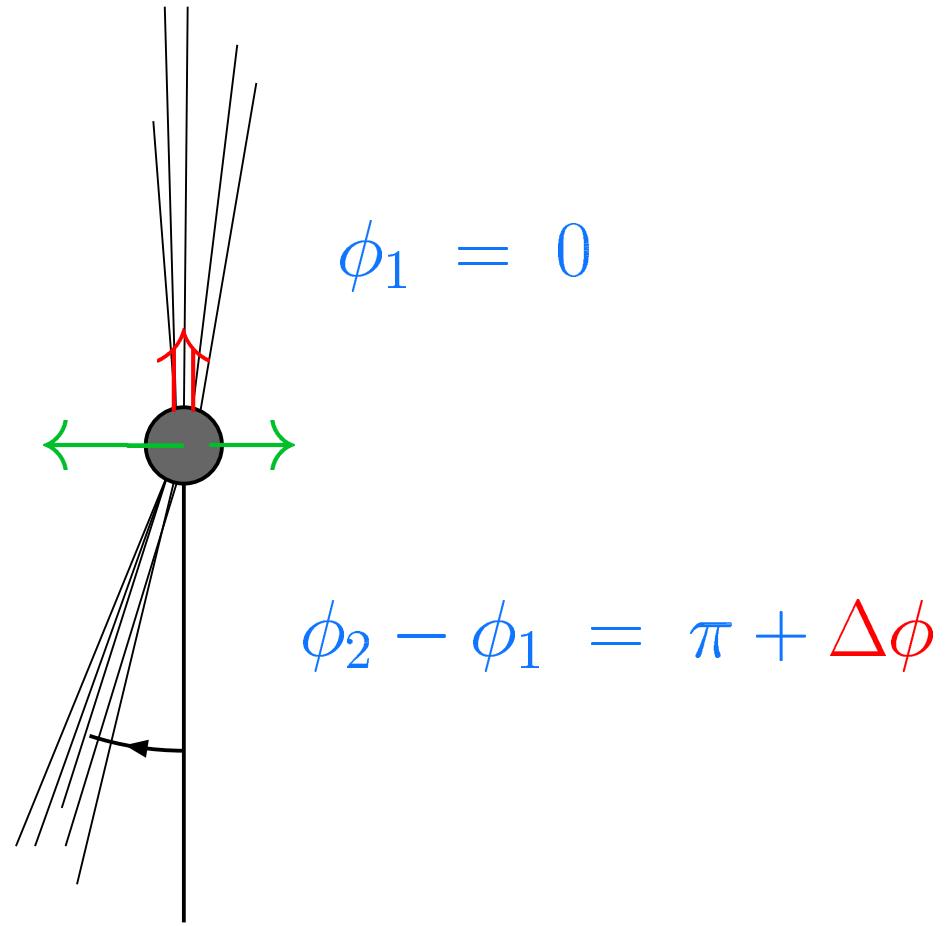
- example : near back-to-back jets in $p^\uparrow p \rightarrow \text{jet jet } X$

Boer,WV





STAR

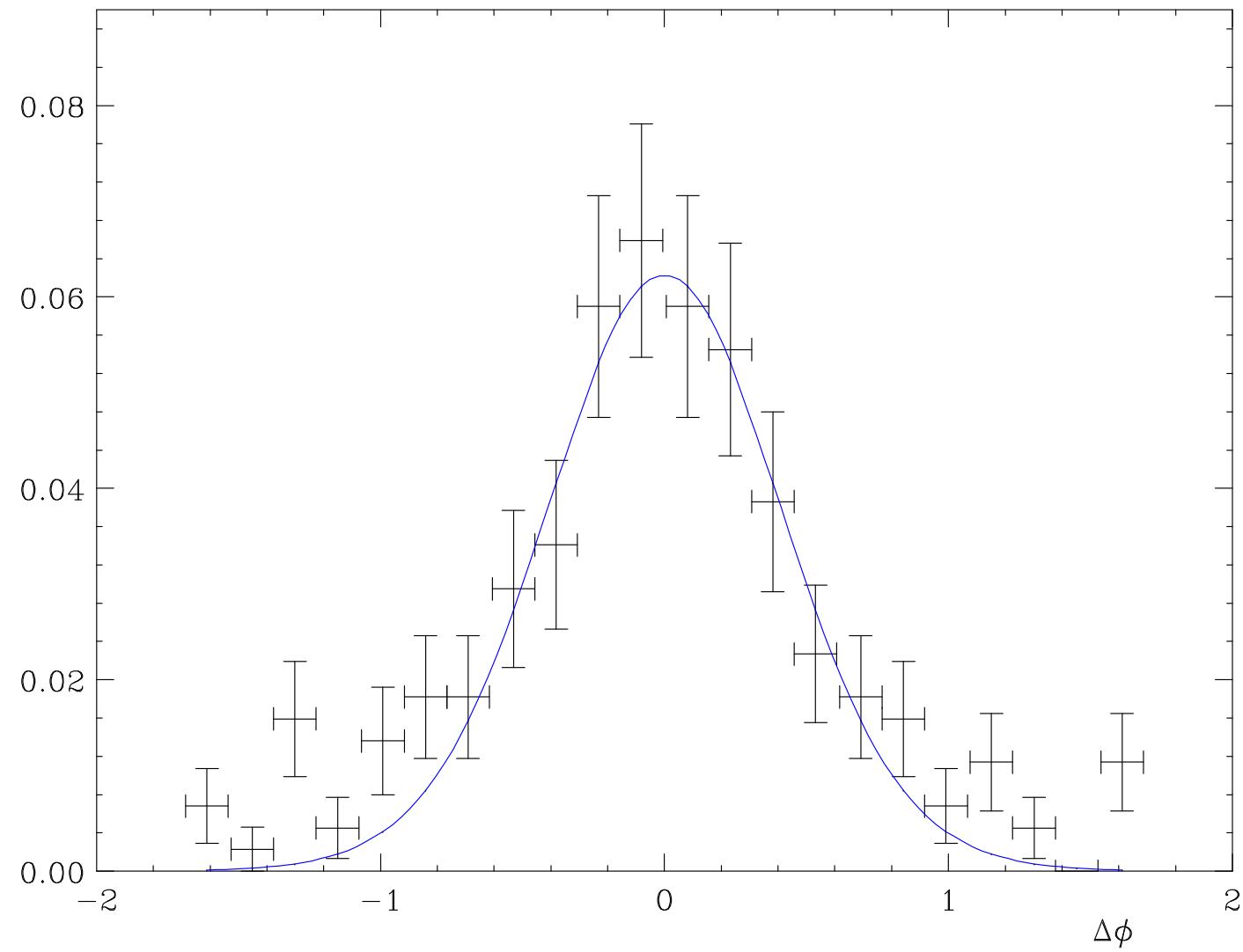


- A simple estimate : Boer,WV
- Gaussian k_\perp distribution for partons in unpolarized proton :

$$f(k_\perp) = \frac{e^{-(k_\perp)^2/\langle k_\perp^2 \rangle}}{\pi \langle k_\perp^2 \rangle} \quad (\text{mostly gluons})$$

- leads to distribution
- $$\propto e^{-a(1-\cos(\Delta\phi))}$$
- fit to STAR back-to-back data :

$$\sqrt{\langle k_\perp^2 \rangle} \approx 1.3 \text{ GeV}$$



- Sivers type correlation :

$$f_{1T}^\perp(k_\perp) \propto k_\perp e^{-(k_\perp)^2/\langle r_\perp^2 \rangle}$$

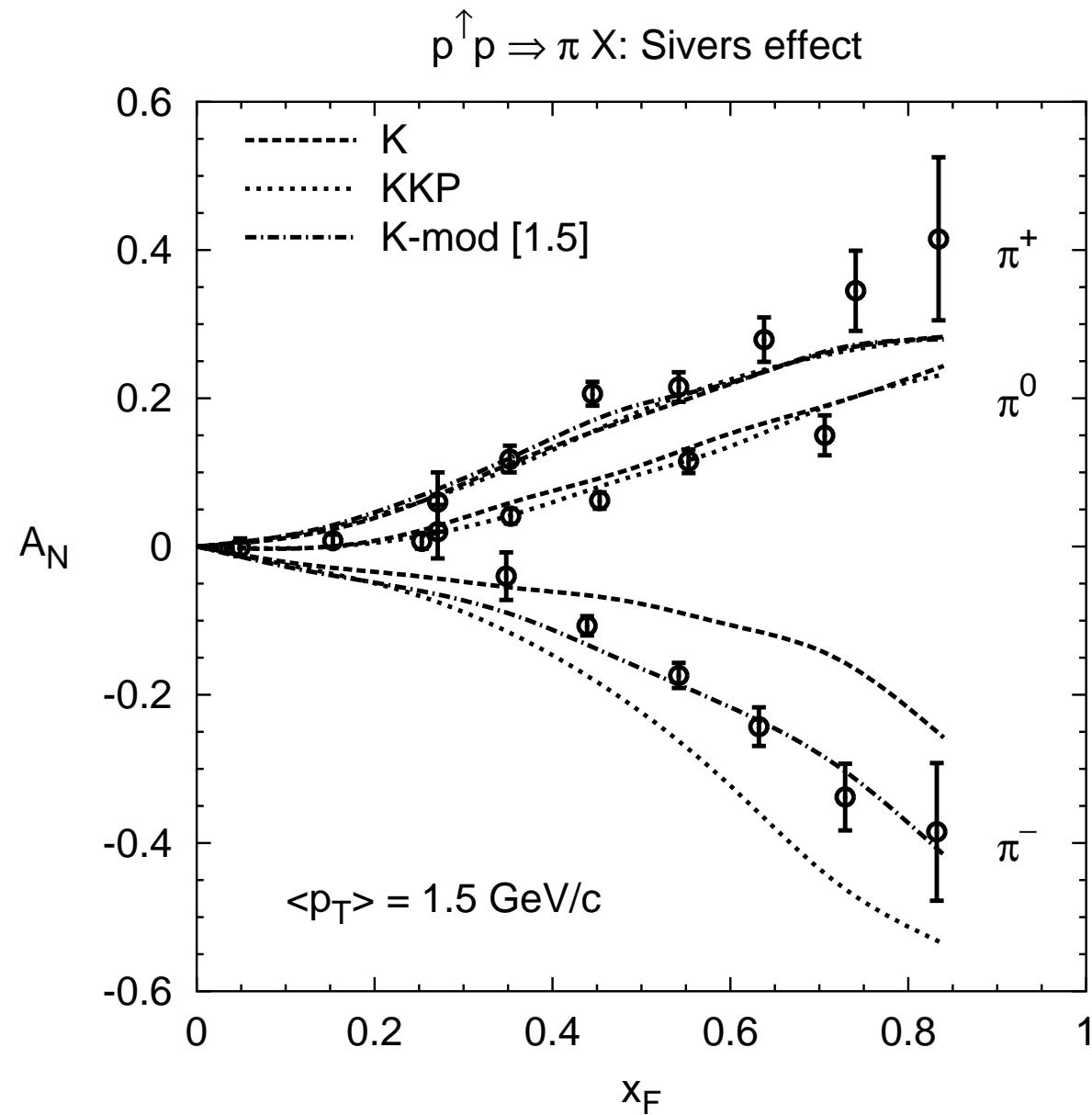
- leads to spin asymmetry

$$A_N \propto \left(|\vec{P}_c^\perp| \sin \phi_c + |\vec{P}_d^\perp| \sin \phi_d \right) \frac{2\langle r_\perp^2 \rangle}{(\langle r_\perp^2 \rangle + \langle k_\perp^2 \rangle)^2} e^{-[\vec{P}_c^\perp + \vec{P}_d^\perp]^2 / (\langle r_\perp^2 \rangle + \langle k_\perp^2 \rangle)}$$

- for $\vec{P}_c^\perp \parallel \vec{S}_\perp$
- $$\propto \sin(\Delta\phi) e^{-a(1-\cos(\Delta\phi))}$$

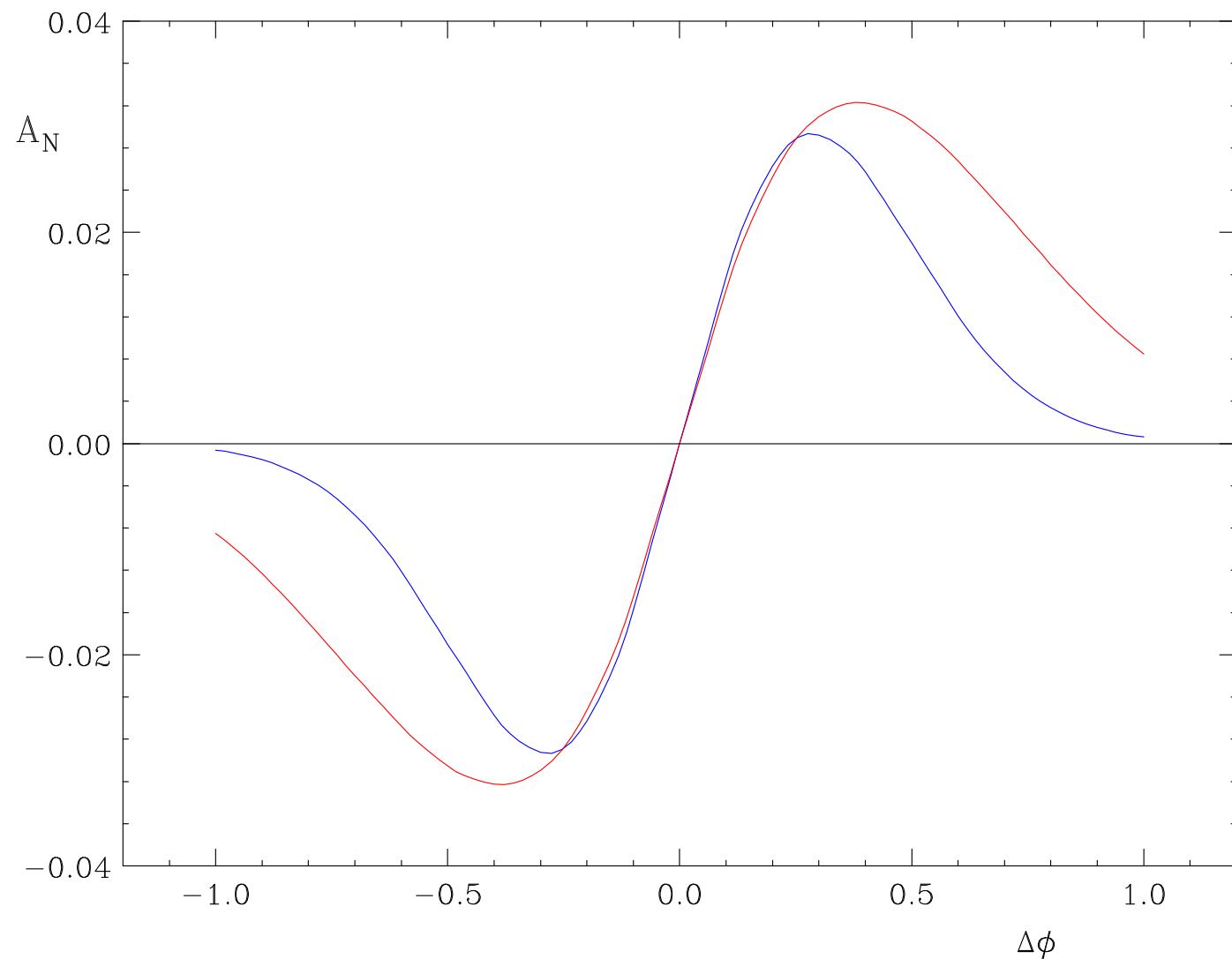
- use parameters of [Anselmino,D'Alesio,Murgia](#)
- very sensitive to [gluon](#) Sivers function
- future : perturbative tail, Sudakov effects

- d'Alesio, Murgia



$\sqrt{S} = 200 \text{ GeV}$, $8 \leq p_{T1,2} \leq 12 \text{ GeV}$, $-1 \leq \eta_{1,2} \leq 1$

Boer,WV



Conclusions :

Δg

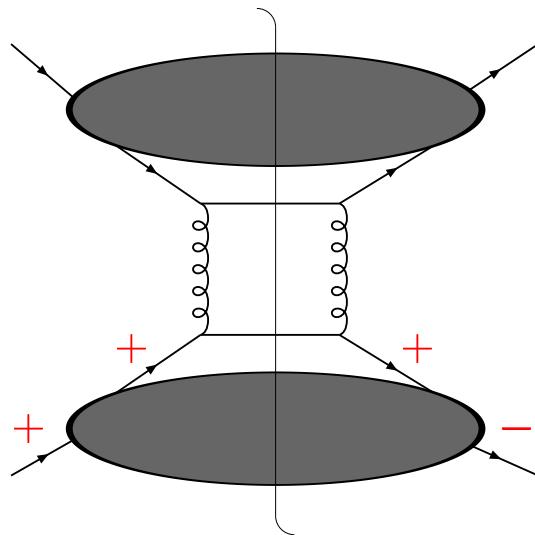
- a lot can be learned from jets and hadrons
- sign of Δg from forward region ?
- most theoretical tools in place – some challenges remain

A_N

- look for $1/p_T$ behavior of $p^\uparrow p \rightarrow \pi X$
- large potential for back-to-back observables

- physics importance of Sivers function :

- * interference of $J_z = +\frac{1}{2}$ and $J_z = -\frac{1}{2}$ amplitudes
 \rightarrow orbital angular momentum



- * Burkardt : connection $q(x, \vec{k}_T) \leftrightarrow q(x, \vec{b}_T) \leftrightarrow H, E$ "GPD's"
- * universality ?

$$f_{1T}^\perp|_{\text{DY}} = -f_{1T}^\perp|_{\text{DIS}}$$

Collins; Brodsky,Hwang,Schmidt;
 Belitsky,Ji,Yuan; Boer,Mulders,Pijlman; Anselmino,D'Alesio,Murgia